Can very massive stars avoid Pair-instability Supernovae ?

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Abstract. Very massive primordial stars (140 $M_\odot$ < M < 260 $M_\odot$) are supposed to end their lives as pair-instability supernovae. Such an event can be traced by a typical chemical signature in low metallicity stars, but at the present time, this signature is lacking in the extremely metal-poor stars we are able to observe. Does it mean that those very massive objects did not form, contrarily to the primordial star formation scenarios? Could they avoid this tragical fate?

We explore the effects of rotation, anisotropic mass loss and magnetic fields on the core size of a very massive Population III model, in order to check if its mass is sufficiently modified to prevent the pair instability.

We obtain that a Population III model of 150 $M_\odot$ with $v/v_{\mathrm{crit}} = 0.56$ computed with the inclusion of wind anisotropy and Tayler-Spruit dynamo avoids the pair instability explosion.

Keywords: Pop III, PISN, rotation, mass loss

WHERE ARE THE PAIR-INSTABILITY SUPERNOVAE ?

According to Heger & al. [1], the fate of single stars depends on their He-core mass (M_α) at the end of the evolution. They have shown that at very low metallicity, the stars having 64 $M_\odot$ < M_α < 133 $M_\odot$ will undergo pair-instability and be entirely disrupted by the subsequent supernova. This mass range in M_α has been related to the initial mass the star must have on the main sequence (MS) through standard evolution models: 140 $M_\odot$ < M_{ini} < 260 $M_\odot$. Since we will present here a non-standard evolution, we will rather keep in mind the M_α range.

The typical mass of Population III (Pop III) stars is explored by early structure formation studies and chemistry considerations about cooling. Different studies (see Abel & al. [2] or Bromm & al. [3] among others) give the same conclusion: Pop III stars are supposed to be massive or very massive, even when a bimodal mass distribution allows the formation of lower mass components (see Nakamura & Umemura [4]). Therefore we expect that many among them should die as pair-instability supernovae (PISN).

A typical chemical signature which remains unobserved

These PISN events are supposed to leave a typical chemical signature. According to Heger & Woosley [5], the complete disruption of the star leads to a very strong odd-even effect: the absence of stable post-He burning stages deprives the star of the neutron excess needed to produce significant amounts of odd-Z nuclei. Also the lack of r- and s-process stops the nucleosynthesis around zinc. Even if one mixes these yields with the yields of zero-metallicity 12 − 40 $M_\odot$ models (which end up as standard Type II SNe), the PISN signature remains and should be observable.

However, using those yields, Tumlinson & al. [6] have shown that it provides only a very poor fit to the abundances pattern observed in the metal-poor stars known today. The odd-even effect is not observed, and the models significantly over-produce Cr and under-produce V, Co and Zn.

The most metal-deficient stars are supposed to be formed in a medium enriched by only one or a few SNe. The absence of the chemical signature of the PISN is a strong argument against their existence. But how could that be?

Simple solutions

The simplest solution to explain this absence is to suppose that the mass domain in question was not formed in the primordial clouds. Maybe the primordial IMF was not as top-heavy as we actually think, and the most massive stars formed then could very well be too small for such a fate. This solution however seems quite unlikely, given the results of the latest works on the primordial star formation (see the contributions in sessions I and II of this conference).

Another possibility is that the signature was very quickly erased by the next generations of stars. Maybe the metal-poor stars we observe are enriched by more SNe than we actually think, and the later contributions are masking the primordial ones. Only the observation of more and more metal-deficient stars will provide an answer to that possibility.

One can also wonder whether there would be a way for those stars to avoid their fate. In this context, the simplest solution is to suppose that some mechanism could lead to such a high mass loss that the conditions for pair-instability would no more be met in the central regions. The aim of the present work is to explore this possibility.

WOULD ROTATION HELP?

We have shown [7] that rotation can change the mass loss history of low metallicity stars in a dramatic way. Two processes are involved:

1. During MS, the low metallicity reduces the radiative winds, so that the star loses very little mass and thus very little angular momentum. As the evolution proceeds, the stellar core contracts and spins up. If a coupling exists between the core and the envelope (*i.e.* meridional currents or magnetic fields), the surface may be accelerated up to the critical velocity and the star may lose mass by a mechanical wind due to centrifugal acceleration. The matter is launched into an equatorial disk and the question which arises is whether the matter may fall back on the star or may really be considered as lost. According to S. Owocki (private communication), the luminosity of the star is well sufficient to dissipate the disk fast enough for the matter to be lost indeed.

2. Rotation induces an internal mixing which enriches the surface in heavy elements. The effective surface metallicity is enhanced by a factor that has been shown to be very large (up to 10^6 for a 60 $M_\odot$ at $Z_{ini} = 10^{-8}$). Rotation also favours a redward evolution after the MS, allowing the star to spend more time in the cooler part of the HR diagram. The opacity of the envelope is increased, and the radiative winds may thus be drastically enhanced.

Both effects add up and lead to strong mass loss at very low metallicity.

Rotation at $Z = 0$

But what happens when the metallicity is not very low but strictly zero ? All the effects described above are present but their amplitude is moderate (see the contribution of Georges Meynet in these proceedings for a more complete description).

The meridional currents are much smaller at $Z = 0$ than at low or very low Z (Fig. 1). The amplitude of the outer cell of the meridional circulation is lower when the envelope is more compact, and may even change sign (reversing the transport of angular momentum) in some
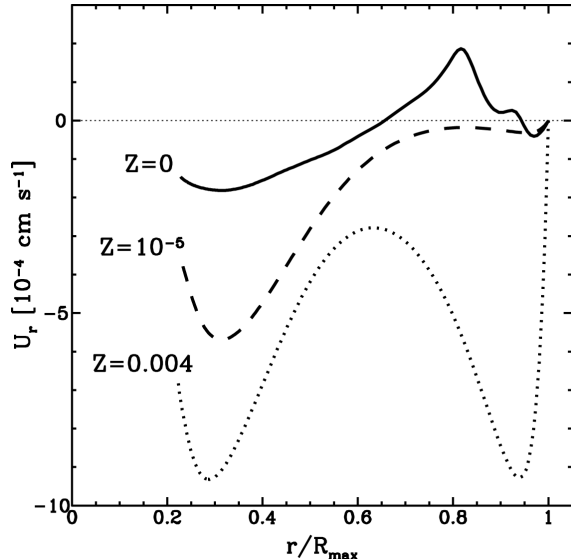

FIGURE 1. Amplitude of the meridional currents in the interior of 20 $M_\odot$ models at the same evolutionary stage ($X_c = 0.40$) but at different metallicities. Continuous line: $Z = 0$; dashed line: $Z = 10^5$; dotted line: $Z = 0.004$.

parts of the star. The stars may reach the critical limit, but later in their MS evolution (for a given initial mass and velocity), and the mechanical mass loss remains thus very small.

After the MS, the redward evolution is delayed because of structural differences: the combustion of helium starts smoothly as soon as the central hydrogen content has been exhausted, without core contraction since the central temperature is already hot enough to sustain the 3-α reaction during the core H-burning phase. The star remains in the blue part of the HR diagram until some carbon is brought by mixing to the H-shell, driving a flash as the shell turns on the CNO-cycle and becomes suddenly convective. Eventually the star reaches the red part of the HR diagram, but the outer convective zone remains very thin, so the surface enrichment is low. The radiative winds are indeed enhanced by the change in opacity, but not much.

Rotation alone seems thus to fail in providing a way to lose sufficient mass at $Z = 0$ for our purpose.

Two natural effects of rotation

In fact, in previous calculations, we have neglected two mechanisms which arise naturally with rotation and which could change this picture.

The first one is the wind anisotropy (see Maeder [8]): when a star rotates fast, it becomes oblate. As shown by von Zeipel's theorem, the poles become hotter than

the equator, and the radiative flux is no more spherically symmetric: it gets much stronger in the polar direction than in the equatorial plane. Since the mass is lost preferentially near the poles, it removes much less angular momentum than in the spherical configuration, and thus the star may reach the critical limit much earlier.

The second mechanism is the magnetic fields. According to Spruit [9] the differential rotation may amplify an existing magnetic field through the Tayler-Spruit dynamo mechanism, and provide a strong core-envelope coupling. This coupling will be able to accelerate the surface very early in the evolution, and maintain the star at critical limit throughout its entire evolution.

MODELIZATION

Ingredients

With the help of the two effects mentioned above, we have computed an exploratory model. Its mass has been chosen to be 150 $M_\odot$ and the initial ratio between the equatorial velocity and the critical one to be $v_{ini}/v_{crit} = 0.56$. Let us mention that this ratio is higher than the one needed to account for the observed average velocities at solar metallicity, but it is still a "reasonable" value, not an extreme one.

The computation has been accomplished using the Geneva code with up to date nuclear reaction rates obtained with NETGEN (http://www-astro.ulb.ac.be/Netgen/). The opacity tables come from OPAL (http://www-phys.llnl.gov/Research/OPAL/opal.html) with the extension at low temperature by Ferguson & al. [10]. The initial composition is $X = 0.753$, $Y = 0.247$ and of course $Z = 0$.

The radiative mass loss prescription is an important ingredient of the modelization of massive stars. Here we have used Kudritzki's [11]. Since this prescription is not aimed at the case $Z = 0$ strictly, we have used the same adaptations as in Marigo & al. [12]. The Wolf-Rayet (WR) mass loss rate is taken from Nugis & Lamers [13] with the metallicity scaling from Eldridge & Vink [14]. For the calculation, we have taken the effective surface metallicity $Z_{eff} = (1 - X - Y)_{surf}$ so that the enrichment of the surface is accounted for. We must stress that this Z_{eff} is mainly composed by CNO elements but no iron. It is usually considered that WR winds are triggered by Fe lines, whereas the CNO lines determine only v_∞, so we expect that no WR winds can take place at $Z = 0$. But Vink & de Koter [15] have shown that when the metallicity gets really low, the CNO lines take over the role of Fe lines in the line driving, and the metallicity dependance of the mass loss flattens.

When the model reaches the critical limit, the mechanical mass loss has been treated as described in [7].

The treatment of anisotropic winds has been implemented as in Maeder [16] and the effect of magnetic fields as in Maeder & Meynet [17].

Evolution and mass loss

In Fig. 2, we present the evolution in the HR diagram (left panel) and the evolution of mass with time (right panel). The grey line shows a non-rotating model computed with the same physics for comparison.

During its whole evolution up to the end of core He-burning, the non-rotating model loses only 1.37 $M_\odot$. This illustrates the weakness of radiative winds at $Z = 0$.

The evolution of the rotating model (black line) can be described by four distinct stages:

1. *(continuous part*, lower left corner) The model starts its evolution on the MS with only radiative winds, losing only a little more than 0.002 $M_\odot$. During this stage, it accelerates quickly because of the strong coupling exerted by the magnetic fields and the minimal loss of angular momentum in the wind.

2. *(dashed part)* When its central content of hydrogen is still 0.58 in mass fraction, it reaches the critical velocity and starts losing mass by mechanical wind. It remains at the critical limit through the whole MS, but the mechanical wind removes only the most superficial layers that have become unbound, and less than 10% of the initial mass is lost at that stage (11.44 $M_\odot$). The model becomes also extremely luminous, and reaches the Eddington limit when 10% of hydrogen remains in the core. As a matter of fact, it is not the classical Γ-limit that is reached here, but the so-called $\Omega\Gamma$-limit. Due to the fast rotation, the maximum Eddington factor allowed is reduced; at the same time, because of the high luminosity, the critical velocity is reduced in comparison with the one derived from the classical Ω-limit (see Maeder & Meynet [18] for details).

3. *(dotted part)* The combustion of helium begins as soon as the hydrogen is exhausted in the core, then the radiative H-burning shell undergoes the CNO flash, setting the model on its redward journey. Whatever the structural modifications, the model remains at the $\Omega\Gamma$-limit and loses a huge amount of mass: if it contracts slightly, the equatorial velocity gets closer from the Ω-limit and matter is expelled; if it expands slightly, the luminosity gets closer to the Γ-limit, reducing the maximal equatorial velocity allowed, and again matter is expelled. The strong magnetic coupling keeps bringing angular momentum to the surface and even the heavy mass loss is
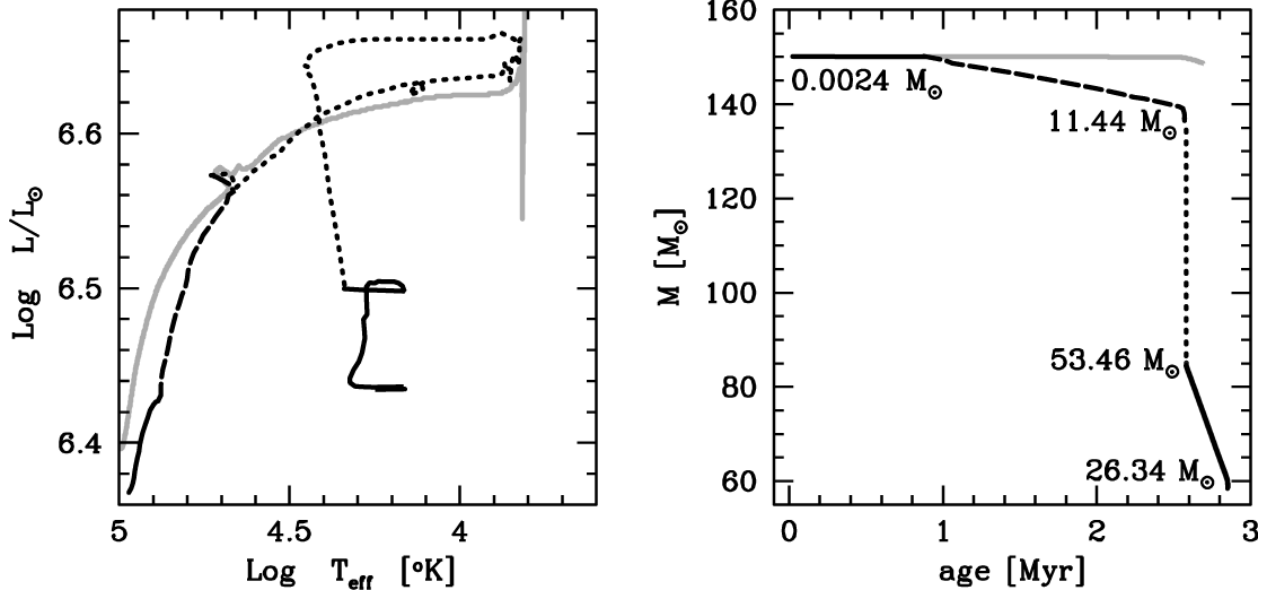
FIGURE 2. Black line: rotating model; *continuous part*: beginning of MS ($X_c = 0.753$ down to 0.58; *dashed part*: rest of the MS; *dotted part*: beginning of core He-burning phase ($Y_c = 1.00$ down to 0.96); *continuous part*: rest of the He-burning. Grey line: non-rotating model for comparison. **Left panel**: evolution in the Hertzsprung-Russell diagram; **Right panel**: evolution of the mass of the model. The mass indicated is the mass lost at each stage, not a summation.

not able to let the model evolve away from the critical limit. The mass lost during that stage amounts to 53.46 $M_\odot$. When the model starts a blue hook in the HR diagram, its surface conditions become those of a WR star: the surface H mass fraction goes down below 0.4 and the T_{eff} gets higher than 10'000 K. The subsequent sudden drop of luminosity takes the model away from the Γ-limit and marks the end of that stage.

4. *(continuous part)* The rest of the core He-burning is spent in the WR conditions. The mass loss is strong but less than in the previous stage: another 26.34 $M_\odot$ are lost.

At the end of core He-burning, the final mass of the model is only $M_{fin} = 58.05\ M_\odot$, already below the minimum M_α needed for PISN ($M_\alpha \geq 64\ M_\odot$). Note that the contraction of the core after helium exhaustion brings the model back to critical velocity, so this value for M_{fin} must be considered as an upper limit.

SUMMARY

The model we presented here is exploratory. We cannot draw general conclusions from it. But our model shows that heavy mass loss is possible even at $Z = 0$, and the answer to our title's question is: *yes, under certain conditions, very massive stars can indeed avoid PISN.*

Some aspects need yet to be clarified, for example the validity of the WR mass loss rate we have used. Can the CNO lines alone really drive a WR wind? In a more general perspective, we still lack a good mass loss recipe for the strict $Z = 0$ case.

A word of caution must also be cast on the inclusion of magnetic fields. The validity of the Tayler-Spruit dynamo is still under debate, and more work need to be done before we may confidently rely on results that have been obtained with the actual treatment. However, magnetic fields do exist (they are observed in stars and pulsars) and the general effect must be a strong core-envelope coupling, whatever the way we treat it.

Anyway, the physics used in the present model is today's "state of the art" and it is interesting to study what can be achieved with it. Our result is encouraging, because the computation has been accomplished with reasonable assumptions:

1. the initial rotation rate used here was fast but not extreme;
2. the mechanisms called upon (anisotropy of the winds and magnetic fields) are not exotic ones, but two natural effects which arise when one treats properly the case of rotation.

After this first step, it will be interesting to explore further the PISN mass range. Higher mass stars should experiment higher mass loss, but would it still be sufficient to help them avoid pair-instabilities? Stay tuned!

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